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NAVWEPS REPORT 8042
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THE EFFECT OF A ROTATING CYLINDER AT THE LEADING AND TRAILING EDGES OF A HYDROFOIL

By
John D. Brooks

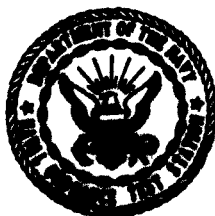
Underwater Ordnance Department

ABSTRACT. An experimental investigation was conducted in the High Speed Water Tunnel at the California Institute of Technology on the lift, drag, and moment produced by a rotating cylinder in the leading and trailing edges of a hydrofoil. It was found that with the cylinder in the leading edge, only a small increase in lift was developed, while with the cylinder in the trailing edge a much larger lift increase was noted.

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FOREWORD

The investigation described in this report was performed as part of a continuing research program in hydrodynamics of controls.

The work was done under Bureau of Naval Weapons Task Assignment RUTO-3D000/216-1/F008-03-001 (Bureau of Ordnance Task Assignment 403-664/41006/02060) during the period from October 1960 to April 1962.

The considered opinions of the Guidance and Control Division are represented in this report.

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NOMENCLATURE

- b Span of hydrofoil, ft
- c Chord of hydrofoil, ft
- C_D Drag coefficient, $C_D = \frac{\text{drag, lb}}{(\rho/2)V^2bc}$
- C_L Lift coefficient, $C_L = \frac{\text{lift, lb}}{(\rho/2)V^2bc}$
- C_M Moment coefficient, $C_M = \frac{\text{moment, ft-lb}}{(\rho/2)V^2bc^2}$
- V Water-tunnel velocity at the model, ft/sec
- w Peripheral velocity of the rotating cylinder, ft/sec
- α Angle of attack, deg
- ρ Density of the fluid, slugs/ft³

INTRODUCTION

When a rotating cylinder advances through a fluid, it experiences a lift force perpendicular to the direction of motion and to the axis of the cylinder. This phenomenon, the well-known Magnus effect, can be used to produce very large lift forces which have been thoroughly investigated experimentally. The primary reasons for failures of practical applications, such as the Flettner Rotor Ship, were the extra equipment required to rotate the cylinder, and the fluid dynamic characteristics of a cylinder, especially undesirable when the cylinder is not rotating.

An application which might avoid these difficulties is the incorporation of a rotating cylinder as either the leading or trailing edge of an airfoil or hydrofoil. Specifically, this report considers the generation of a lifting force to control underwater vehicles that would take the form of a low-aspect-ratio hydrofoil (similar to a torpedo fin) fitted with a rotating cylinder at the nose and having a sharp trailing edge. This report also considers a hydrofoil with a rounded, streamlined nose and a rotating cylinder at the trailing edge. A hydrofoil with a rotating cylinder in the leading edge might have the following advantages over conventional control surfaces:

1. Simplicity of electrical actuation, since the cylinder could be driven directly by an electric motor, without the gear train that is needed for actuation of conventional control surfaces
2. Proportional control by variation of motor speed
3. Possible reduction in complexity and size, by incorporation of a flooded electric motor within the cylinder, which would eliminate the sealing problem

Possible disadvantages would be

1. Relatively low lift resulting from cylinder rotation
2. Decreased resistance to cavitation
3. Relatively slow response time

In the case of the rotating cylinder in the trailing edge of the fin, a relatively high lift resulting from rotation might be expected. The cylinder in the rear position would have the same general advantages and disadvantages as in the forward position, but would have the added disadvantage of high drag when the cylinder is not rotating.

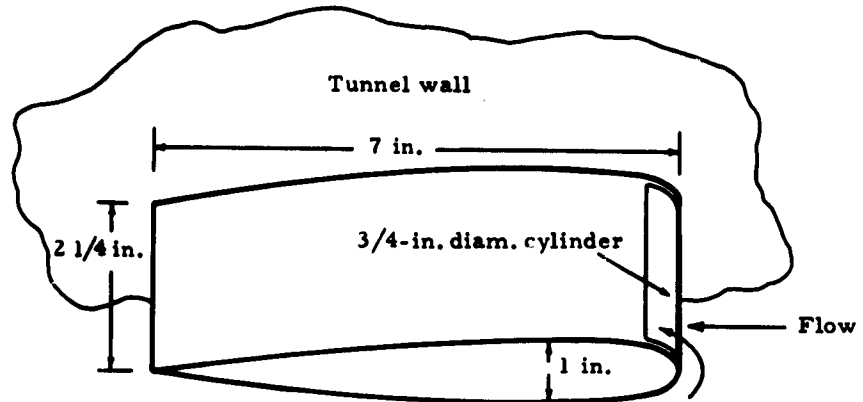
In practice, the most efficient design would employ a relatively large cylinder if mounted in the leading edge, but a small one if mounted in the trailing edge, to minimize the disadvantages of each location.

The amount of lift realized on the cylinder-hydrofoil combination depends on the circulation induced by cylinder rotation. Attempts at a theoretical estimate, using airfoil theory, were unsuccessful, primarily because the circulation is caused by the effect of the rotating cylinder on the boundary layer. Since the perfect fluid theory upon which airfoil theory is based postulates inviscid flow, there is no boundary layer and hence neither circulation nor lift. Consequently, a program was initiated in the High Speed Water Tunnel of the California Institute of Technology to obtain experimental data which could be used to determine the feasibility of rotating cylinder control.

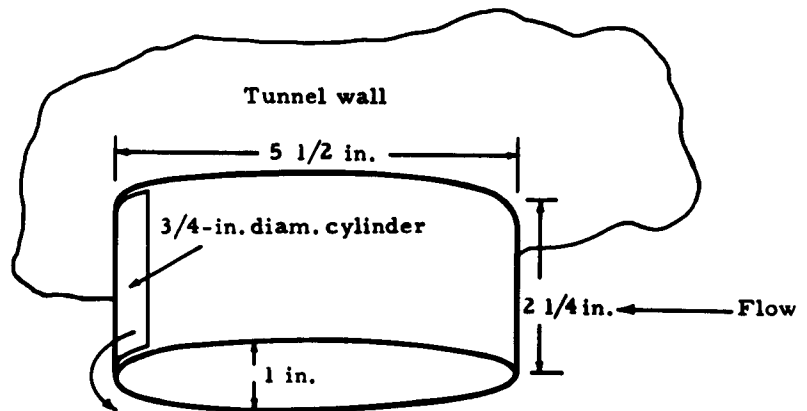
WATER TUNNEL TESTS

Rotating cylinders installed in the leading and trailing edges of a low-aspect-ratio hydrofoil were tested in the High Speed Water Tunnel at the Hydrodynamics Laboratory of the California Institute of Technology.¹ A hydrofoil of an aspect ratio less than one was chosen because low aspect ratio fins are usually used to stabilize and control underwater vehicles. Since the water tunnel has a working section approximately 1 foot in diameter, a hydrofoil of about 1-inch thickness was considered appropriate to avoid wall effects. An image reflection plane was placed along one side of the test section and the hydrofoils were attached to a balance spindle flush with the plane. Figure 1a shows the principal dimensions of the model used to test the rotating cylinder at the leading edge. The section shape of the hydrofoil consisted of the 3/4-inch diameter cylinder as the leading edge, an ogival fairing connecting this to a short parallel section of 1-inch thickness, and an ogival portion extending from the parallel section to the sharp trailing edge. The ogival fairing forming the forward end of the hydrofoil began at the maximum diameter of the cylinder, and at that point the clearance between the cylinder and the hydrofoil was minimum (about 0.007 inch). At the centerline of the cylinder - hydrofoil combination the clearance reached a maximum of 0.06-inch. To avoid the time and expense required to make a new model for tests of the cylinder at the trailing edge, the model shown in Fig. 1a was modified to the configuration shown in Fig. 1b after the first tests were completed. The only change required was to cut off the former trailing edge to form a round nose of 9/32-inch radius. Interchangeable rotating cylinders with three different surface finishes (smooth, grooved, and

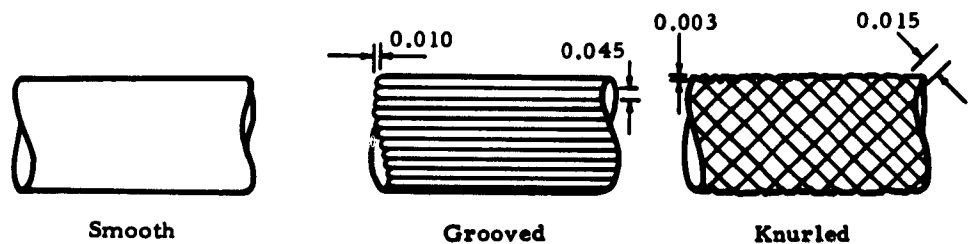
¹ California Institute of Technology. Water-Tunnel Tests of a Hydrofoil With a Rotating Cylinder at the Leading Edge, by Taras Kiceniuk and Harry Hamaguchi. Pasadena, Calif., CIT, March 1962 (Part 1), April 1962 (Part 2). (Internal Memorandum E108.11M.)



(a) Rotating cylinder at leading edge



(b) Rotating cylinder at trailing edge



(c) Cylinder surface finishes

FIG. 1. Water-Tunnel Models.

knurled) were tested. The approximate dimensions of these cylinder surfaces are shown in Fig. 1c. The cylinders were driven by a small d. c. motor capable of speeds to 20,000 rpm and power outputs of about 1/5 hp.

Two nominal tunnel velocities, 30 and 50 fps, were used. The angle of attack of the hydrofoil was varied from -2° to $+2^\circ$ in steps of 1° . Lift, drag, and moment were measured. At the same time cylinder rotative speed was measured stroboscopically, and voltage and current input to the motor were recorded. Measurements on the hydrofoil with cylinder in the forward position were made at the two tunnel velocities for different angles of attack, cylinder speeds, and cylinder roughnesses.

For the tests with the cylinder at the trailing edge, a somewhat abbreviated program was used. In both cases, cavitation characteristics were observed over the range of test conditions. When lift, drag, and moment measurements were made, sufficient tunnel pressure was maintained to prevent cavitation.

TEST RESULTS

The reduced data obtained are presented graphically in Fig. 2 through 15. No water tunnel corrections were applied to the data since the hydrofoil model was small in comparison to the tunnel working-section area.

The power required to drive the rotating cylinder at the leading edge is shown in Fig. 2 as a function of cylinder rotative speed for various conditions of cylinder roughness and tunnel speed. The grooved and knurled cylinders required about the same power, which was considerably more than that required by the smooth cylinder at the same rpm. Furthermore, no significant increase in power was required with increased tunnel velocity, for any of the three roughness conditions tested. Figure 3 shows that similar conclusions can be drawn when the rotating cylinder is at the trailing edge.

With the rotating cylinder in place but not rotating, the lift coefficient of the hydrofoil (C_L) is proportional to the angle of attack, α , as illustrated by Fig. 4 for the smooth cylinder in the leading edge and by Fig. 5 for the cylinder in the trailing edge. Also shown for both cases is lift coefficient versus angle of attack for a large value of w/V , the ratio of cylinder peripheral speed to tunnel velocity. The resulting straight line is parallel to the line for no cylinder rotation, indicating that the effects of rotative speed and angle of attack are independent and can be added linearly. This was true for all cylinder roughnesses tested. It is also apparent from Fig. 4 and 5 that much greater lift is obtained from the rotating cylinder in the rear position than in the forward position.

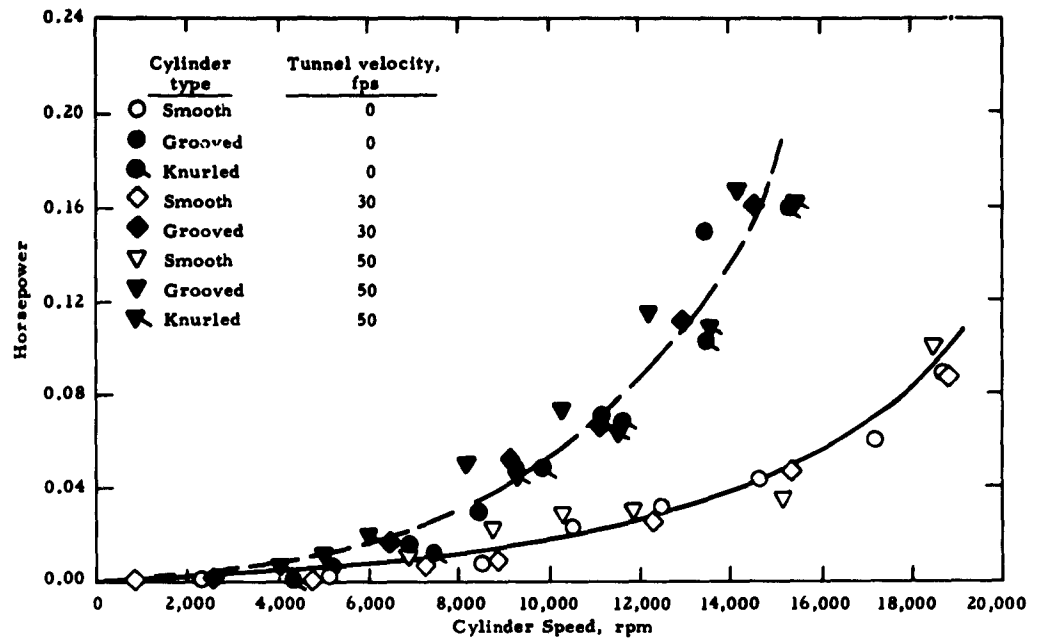


FIG. 2. Cylinder at Leading Edge, HP Versus Cylinder Speed.

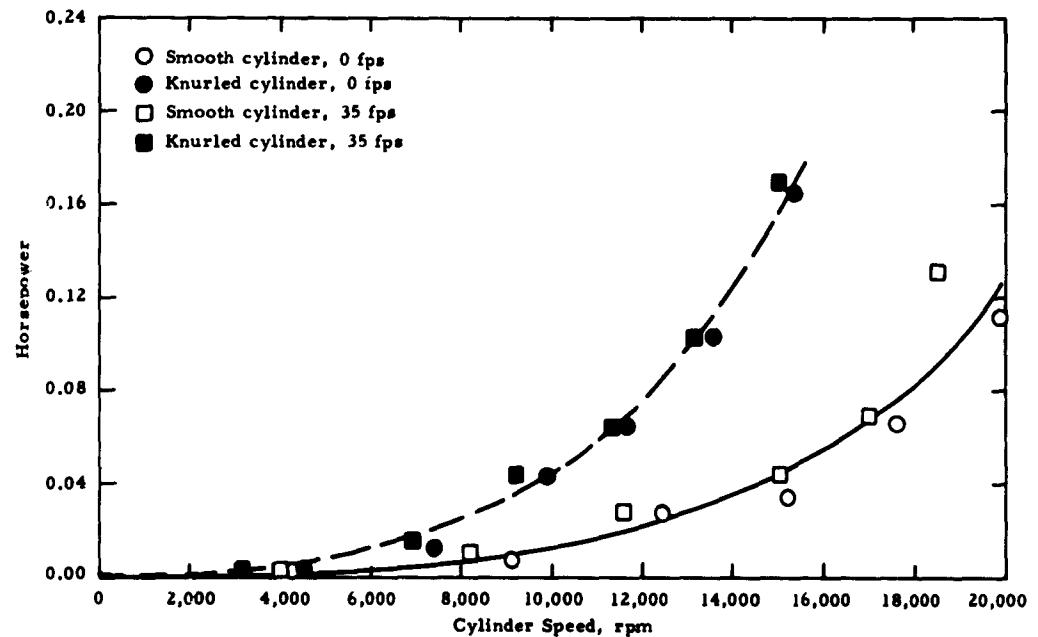


FIG. 3. Cylinder at Trailing Edge, HP Versus Cylinder Speed.

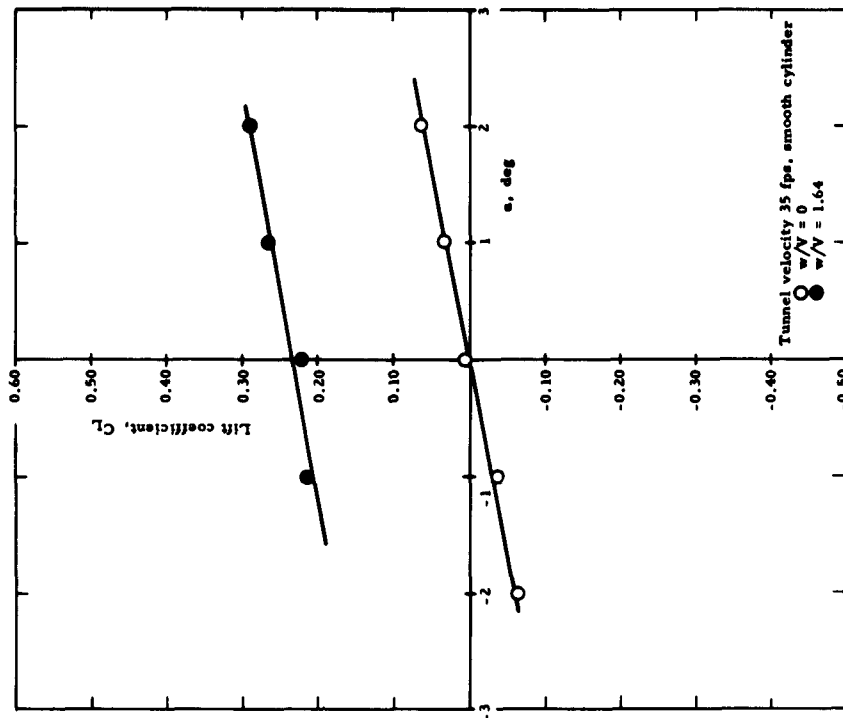


FIG. 5. Cylinder at Trailing Edge, Lift Coefficient Versus Angle of Attack.

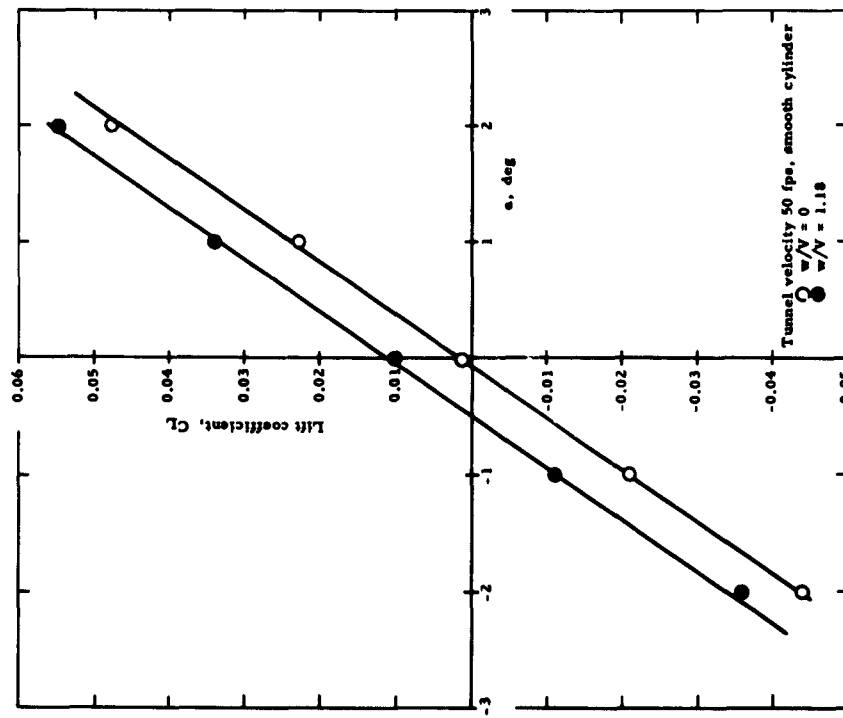


FIG. 4. Cylinder at Leading Edge, Lift Coefficient Versus Angle of Attack.

Figures 6 and 7 show the moment coefficient versus the angle of attack, which is also linear with or without cylinder rotation. Since the lines are approximately parallel, it can be concluded that the moments are also independent and can be added linearly. The moment coefficient is defined about the cylinder centerline, positive counter-clockwise when facing the tunnel wall to which the balance is mounted, hence the negative slope shown in Fig. 6 indicates that the center of pressure is to the rear of the cylinder centerline for the cylinder in the forward position. For the cylinder in the rear position (Fig. 7) the moment coefficient has a positive slope with angle of attack, indicating that the center of pressure is forward of the cylinder centerline.

In Fig. 8 and 9, the curves of drag coefficient (C_D) with no cylinder rotation exhibit an increase with angle of attack for both positive and negative attack angles, and are approximately symmetrical about the zero angle of attack point.

With the cylinder at the leading edge (Fig. 8) and for a high value of rotative speed, the drag coefficient curve is asymmetrical, with the curve in the positive angle of attack quadrant lower than that in the negative angle of attack quadrant. Just the opposite effect seems to be present for the cylinder in the trailing edge (Fig. 9). These effects can be explained by the counterclockwise direction of rotation of the cylinder looking toward the motor. In the first case, the peripheral velocity adds to the tunnel velocity on the upper part of the cylinder (at the leading edge), tending to reduce the boundary-layer separation that is most likely to occur there with positive angle of attack. In the second case, the peripheral velocity subtracts from the tunnel velocity on the lower side of the cylinder (at the trailing edge), which seems to increase the tendency toward boundary-layer separation behind the cylinder. As might be expected, the effect seems to be stronger and more regular in Fig. 8 than in Fig. 9. It is also noteworthy that the drag increase with cylinder rotation is much higher for the cylinder at the trailing edge than at the leading edge. This is probably caused by the much higher lift generated with the cylinder in the rear position, an "induced drag" effect.

The lift, drag, and moment coefficients shown in Fig. 10 to 15 do not include the effect of angle of attack, in order to show more clearly the variation with peripheral velocity. The manner in which lift coefficient increases with the ratio of peripheral velocity to tunnel velocity is illustrated in Fig. 10 and 11. When the cylinder is at the leading edge (Fig. 10) the lift coefficient increases with the velocity ratio, then levels out and becomes approximately constant beyond a velocity ratio of about one. The rough cylinders in this case create greater lift than the smooth cylinder at the lower velocity ratios, but beyond velocity ratio one there is no appreciable difference.

A reasonable explanation for these phenomena is that cylinder rotation causes the effective forward stagnation point to rotate around to the bottom of the hydrofoil. The rough cylinders are more effective

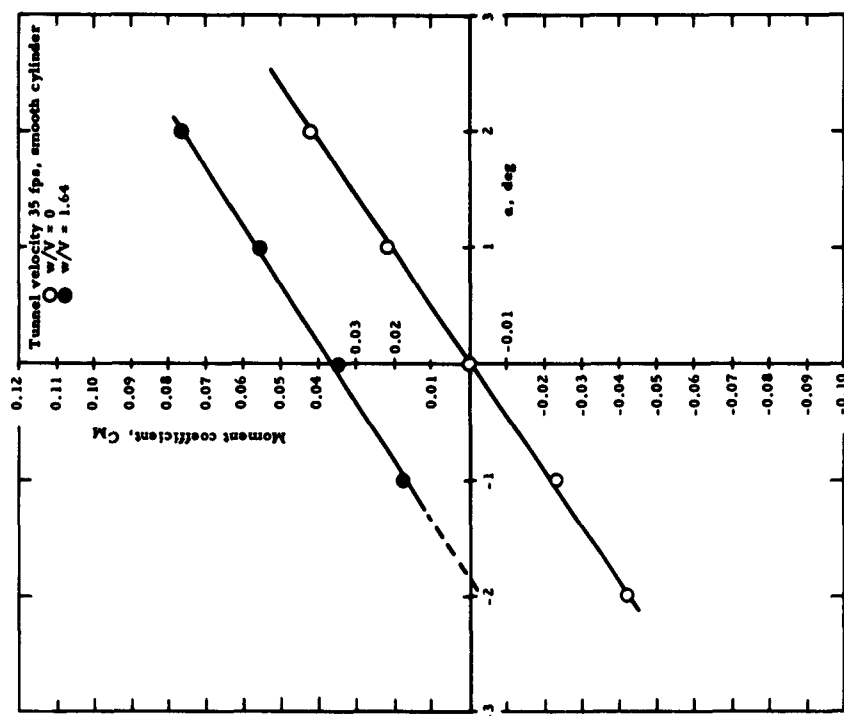


FIG. 7. Cylinder at Trailing Edge, Moment Coefficient Versus Angle of Attack.

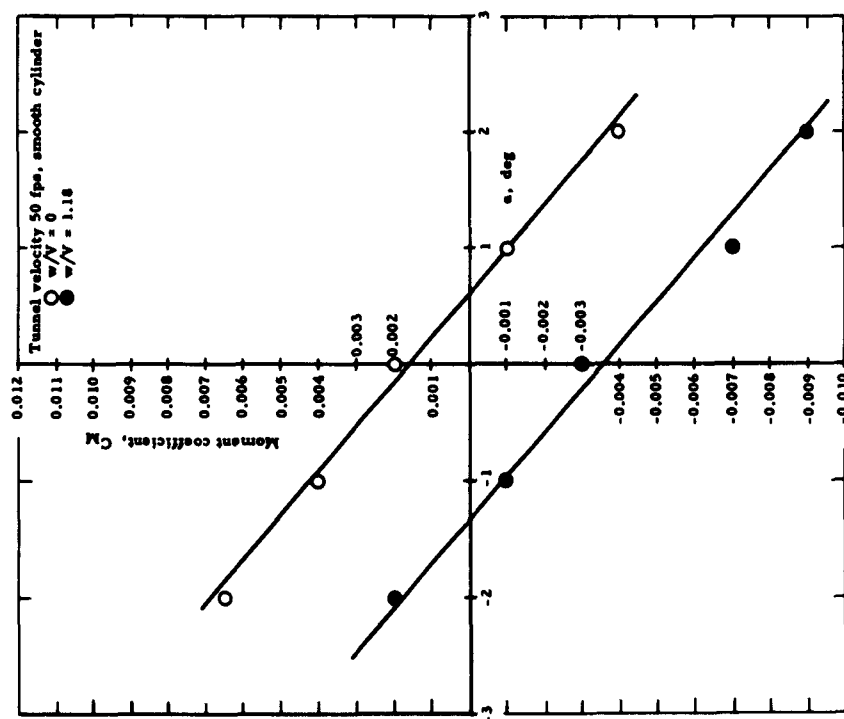


FIG. 6. Cylinder at Leading Edge, Moment Coefficient Versus Angle of Attack.

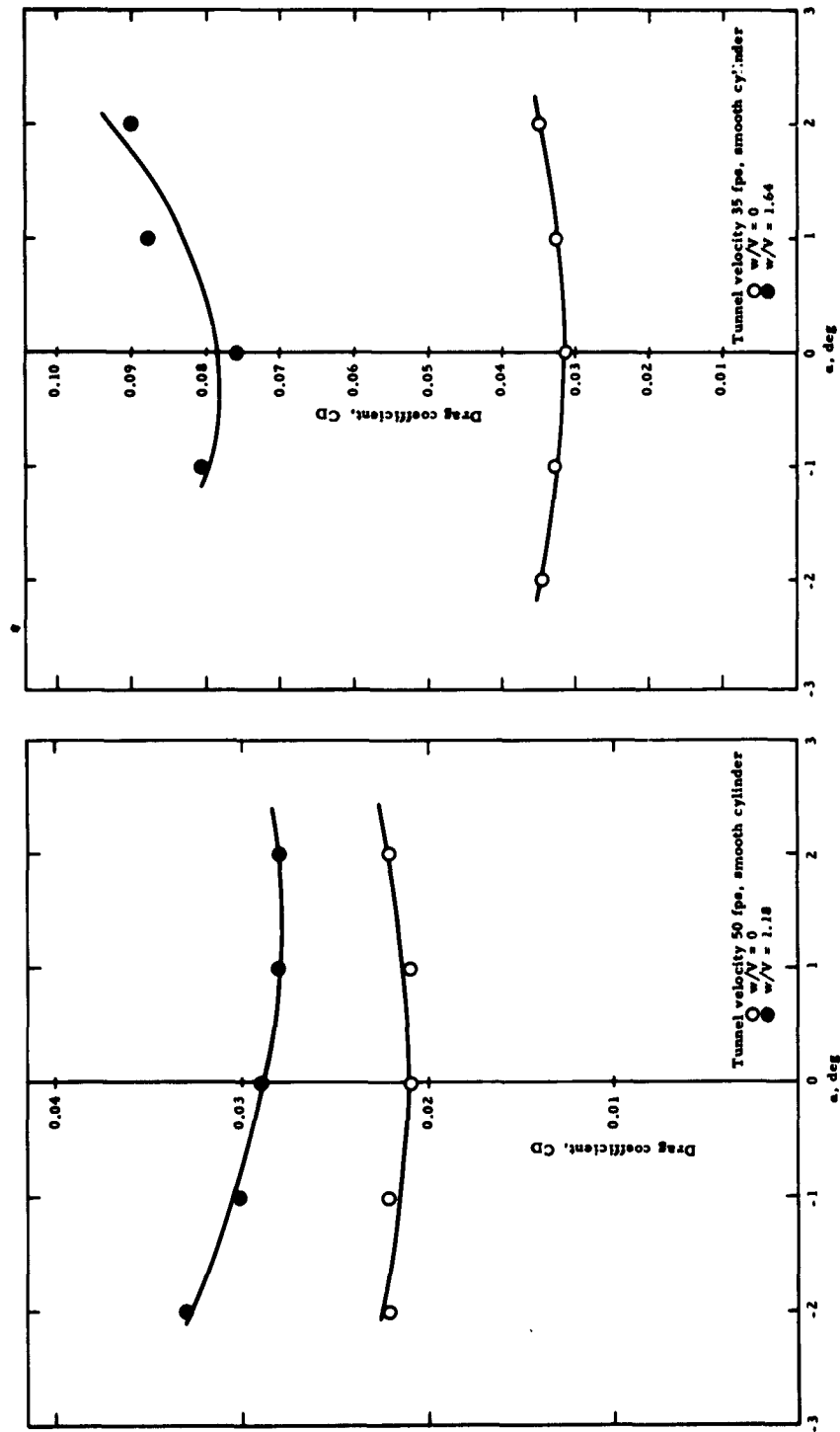


FIG. 9. Cylinder at Trailing Edge, Drag Coefficient Versus Angle of Attack.

FIG. 8. Cylinder at Leading Edge, Drag Coefficient Versus Angle of Attack.

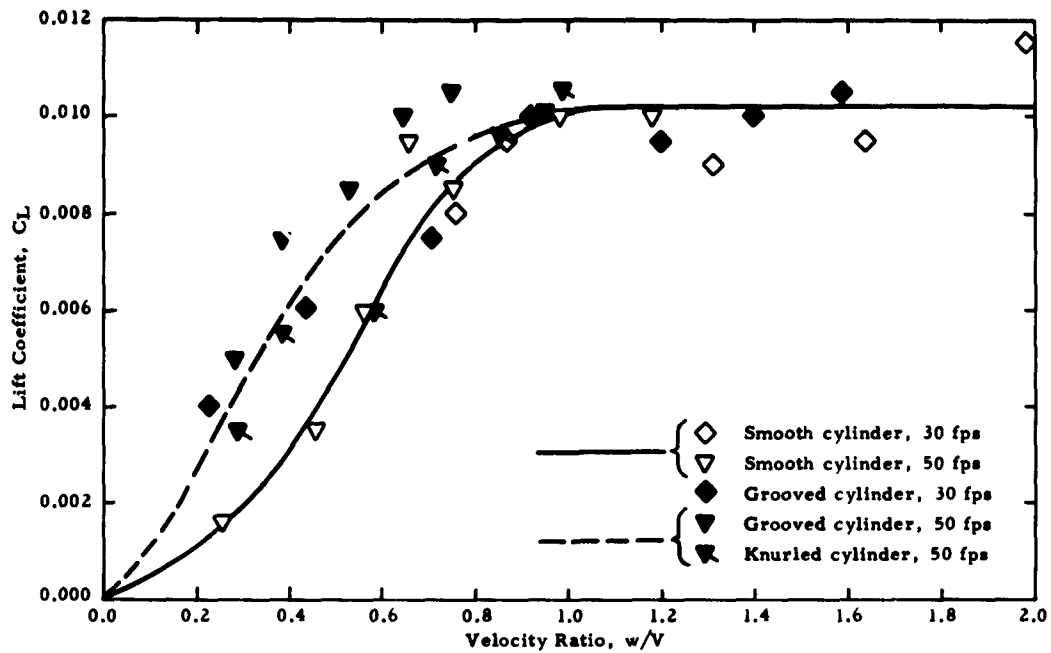


FIG. 10. Cylinder at Leading Edge, Increase in Lift Coefficient Versus Velocity Ratio.

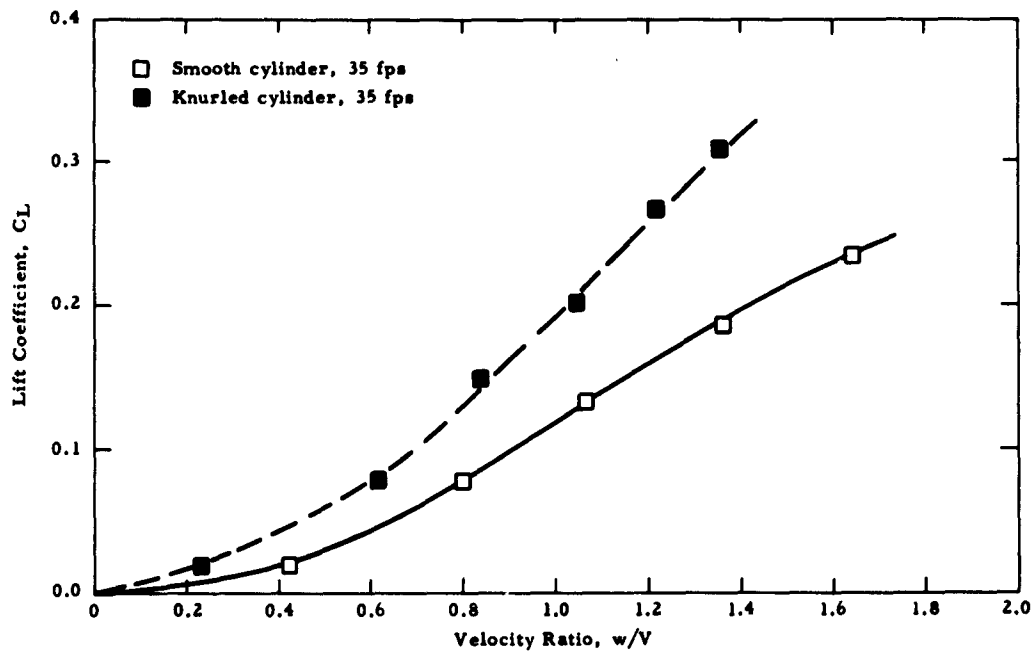


FIG. 11. Cylinder at Trailing Edge, Increase in Lift Coefficient Versus Velocity Ratio.

in causing this rotation than the smooth one. When the effective forward stagnation point reaches the solid lip of the hydrofoil adjacent to the cylinder, no further significant lift increase occurs. With the cylinder at the trailing edge (Fig. 11) the lift coefficient continues to increase with the velocity ratio up to the maximum ratio tested. The rough cylinder also creates greater lift than the smooth one. A possible explanation is that, due to the thick boundary layer at the rear of the hydrofoil, the effective trailing-edge stagnation point was not rotated around as far as the lip, over the range of velocity ratio tested.

One important conclusion to be drawn from Fig. 10 and 11 is that placing the rotation cylinder in the rear position creates at least thirty times more lift than placing it in the forward position. This seems physically reasonable since the cylinder at the rear can not only deflect the flow around it, but also can cause circulation in the vicinity of the rounded hydrofoil nose. On the other hand the cylinder at the leading edge can have only a small effect on the flow at the rear, because of the sharp trailing edge.

The moment coefficient curves in Fig. 12 and 13 can be explained qualitatively on the basis of the moment (C_M) being the lift from Fig. 10 and 11 multiplied by the appropriate center of pressure.

The relationship between drag coefficient and velocity ratio is shown in Fig. 14 for the cylinder at the leading edge, and in Fig. 15 for the cylinder at the trailing edge. In Fig. 14, it can be seen that because of the thin boundary layer at the leading edge, the rough cylinders cause higher drag than the smooth one for all velocity ratios. The change in drag coefficient with velocity ratio, in this case first essentially constant, then increasing with velocity ratio, then remaining at a constant level with further increase in velocity ratio, is probably caused by the increase in drag due to lift. The behavior of the curves in Fig. 15 can also be considered as due to the drag due to lift, and is qualitatively consistent with the observed change in lift with velocity ratio for this configuration.

Although the tests were not conducted primarily to determine cavitation characteristics, and the hydrofoil-cylinder combinations were not designed to be particularly cavitation resistant, incipient and cut-off cavitation numbers were recorded. Considerable variation in cavitation number was noted with variation in Reynolds number, and there were large differences between cut-off and incipient cavitation numbers. There was no consistent variation, however, with cylinder roughness. For the cylinder at the leading edge, with no rotation, the cavitation number, σ , was generally in the range $\sigma = 2$ to $\sigma = 2.5$. With high rotative speed, this increased to $\sigma = 3.0$ to $\sigma = 3.5$. For the cylinder at the trailing edge, with no rotative speed, the cavitation numbers were about $\sigma = 1.5$ to $\sigma = 2.0$. At high rotative speed in this position, σ ranged from approximately 3.0 to 4.0. Cavitation began

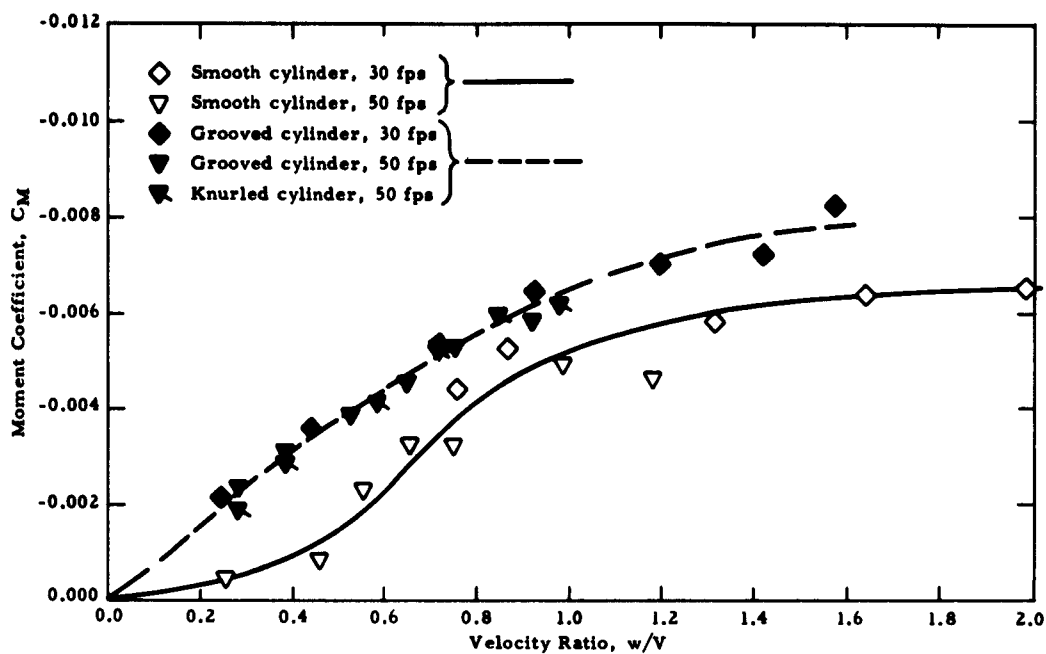


FIG. 12. Cylinder at Leading Edge, Increase in Moment Coefficient Versus Velocity Ratio.

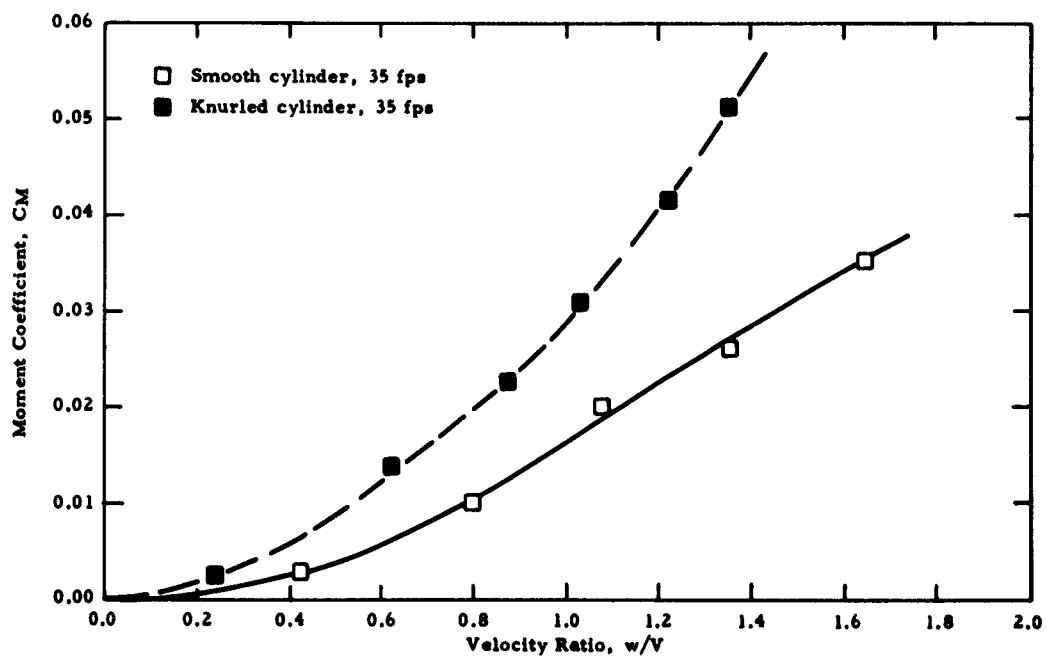


FIG. 13. Cylinder at Trailing Edge, Increase in Moment Coefficient Versus Velocity Ratio.

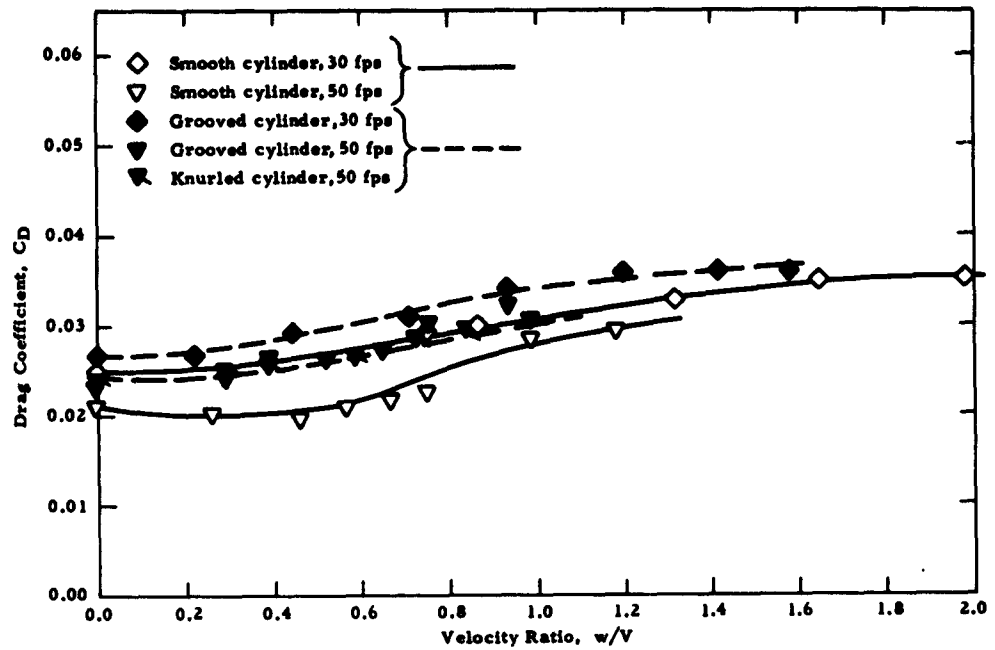


FIG. 14. Cylinder at Leading Edge, Increase in Drag Coefficient Versus Velocity Ratio.

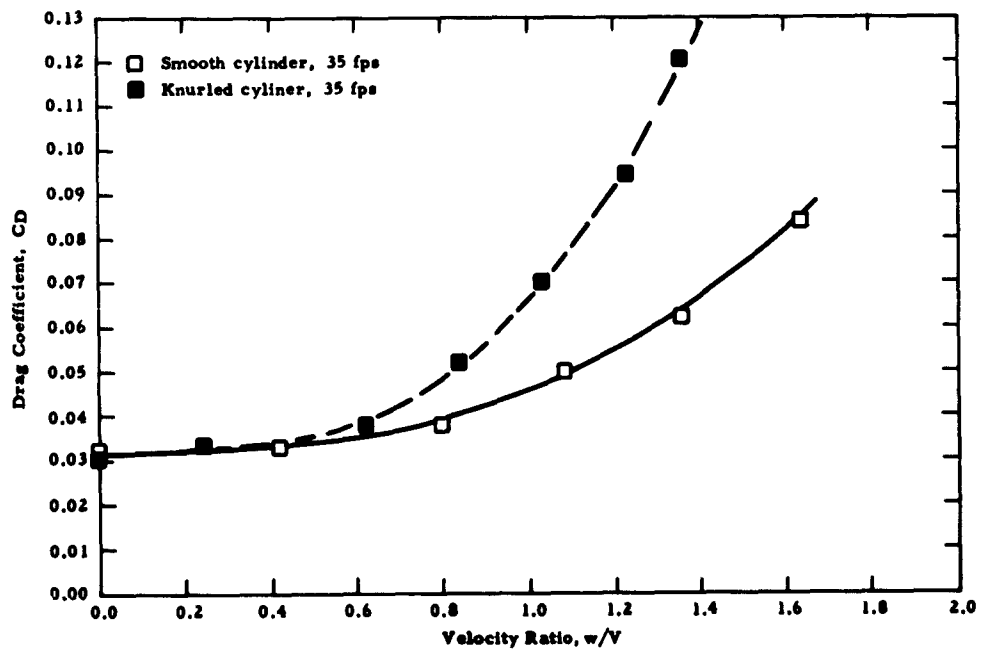


FIG. 15. Cylinder at Trailing Edge, Increase in Drag Coefficient Versus Velocity Ratio.

at the sharp lip of the hydrofoil body near the rotating cylinder and at the forward outer edge of the hydrofoil, which was not sufficiently rounded to avoid cavitation.

CONCLUSIONS

The amount of lift generated with the rotating cylinder in the forward position was disappointing. With an expenditure of about 1/10 hp to rotate the cylinder, only slightly more than 1 pound of lift was developed at 35 fps forward speed. This is equivalent to the lift developed by the hydrofoil without the rotating cylinder when it is placed at less than $1/2^\circ$ angle of attack. Consequently this method of generating control forces does not appear to be practical for torpedoes or other underwater vehicles.

With the rotating cylinder in the rear position, much greater lift was generated. In this case 1/10 hp used to rotate the cylinder produced 25 pounds of lift at 35 fps. This approximates the lift produced by a standard hydrofoil of equal size placed at about 9° angle of attack. This is enough force for the control of most torpedoes or other underwater vehicles. However, the relatively high drag, poor cavitation characteristics, and fairly slow cylinder response time militate against the use of this method to control torpedoes. However, this type of control may have possibilities if applied to other vehicles such as deep research submarines or recovery devices, where simplicity, reliability, and proportionality are more important than drag and cavitation.

ABSTRACT CARD

<p>U. S. Naval Ordnance Test Station The Effect of a Rotating Cylinder at the Leading and Trailing Edges of a Hydrofoil, by John D. Brooks. China Lake, Calif., NOTS, April 1963. 14 pp. (NAVWEPS Report 8042, NOTS TP 3036), UNCLASSIFIED.</p>	<p>U. S. Naval Ordnance Test Station The Effect of a Rotating Cylinder at the Leading and Trailing Edges of a Hydrofoil, by John D. Brooks. China Lake, Calif., NOTS, April 1963. 14 pp. (NAVWEPS Report 8042, NOTS TP 3036), UNCLASSIFIED.</p>
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